LANSCE DIVISION RESEARCH REVIEW

Proton Radiography of High-Explosive Spall in Selected Metals

D.B. Holtkamp, D.A. Clark, D. Martinez, K.C. Forman, R.A Gallegos, V.H. Holmes, K.B. Morley, P.D. Pazuchanics, A. Saunders, G.E. Hogan, F.E. Merrill, C. Morris, M.M. Murray (P Division), M. Garcia, H.L. Stacy, E.N. Ferm, W.F. Hemsing, K.P. Prestridge, M.A. Shinas, R.P. Lopez, (DX Division), R. Liljestrand, T. Schafer (Bechtel Nevada)

When a pressure wave produced by a high-explosive (HE) detonation reaches the free surface of most metals, two different phenomena can occur: (1) one or more layers of solid material is produced from the fracture of the metal and accelerated "spall" or (2) the metal is melted and accelerated to fairly high velocities (1 to 2 km/s). The detailed understanding of spall phenomena in metals is an active area of research in shock physics but also in materials science and microstructural modeling and is of significant interest to both applied and basic science. We undertook a series of proton radiography (pRad) experiments at the Los Alamos Neutron Science Center (LANSCE) in the summer of 2001 to study HE-induced spall in several metals, including copper, aluminum 6061, tantalum, and tin. These experiments used the pRad Facility in Area C.[1] Analysis of the imagery obtained continues, but several important observations can be deduced from the data: (a) it appears that the pRad technique can produce data on the thickness and velocity of multiple layers of spall (up to 8 layers deep in copper); (b) although the first few layers appear to be quite reproducible, as one goes deeper into the damaged metal the phenomenology becomes "noisier" with a more statistical nature to the layering, at least in this HE/target geometry; and (c) when material is melted on shock, it is readily visible in the proton radiographs (e.g., tin) and information can be obtained on the velocity distribution of the melted material.

Results of the pRad Study

The basic configuration of the experiment is shown in Fig. 1. A 2-in.-diam, 0.5-in.-thick cylinder of HE (PBX9501) is initiated with an SE-1 detonator

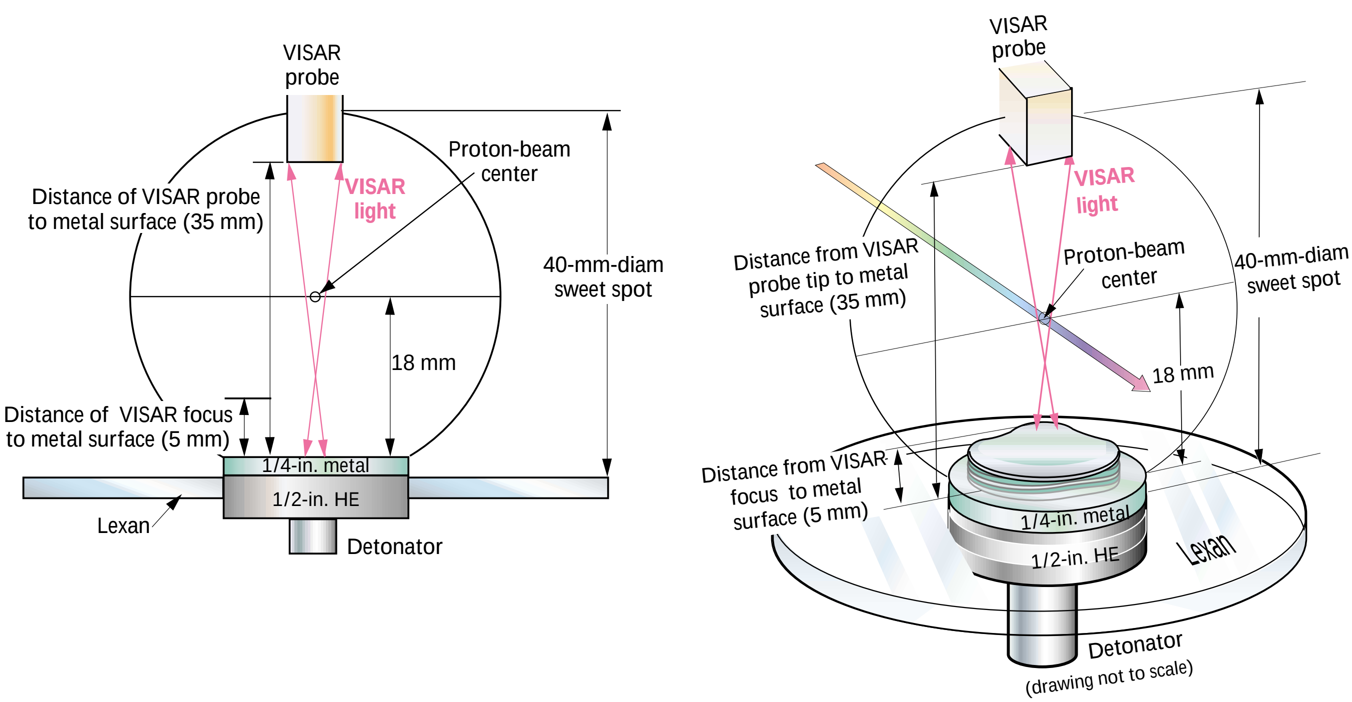
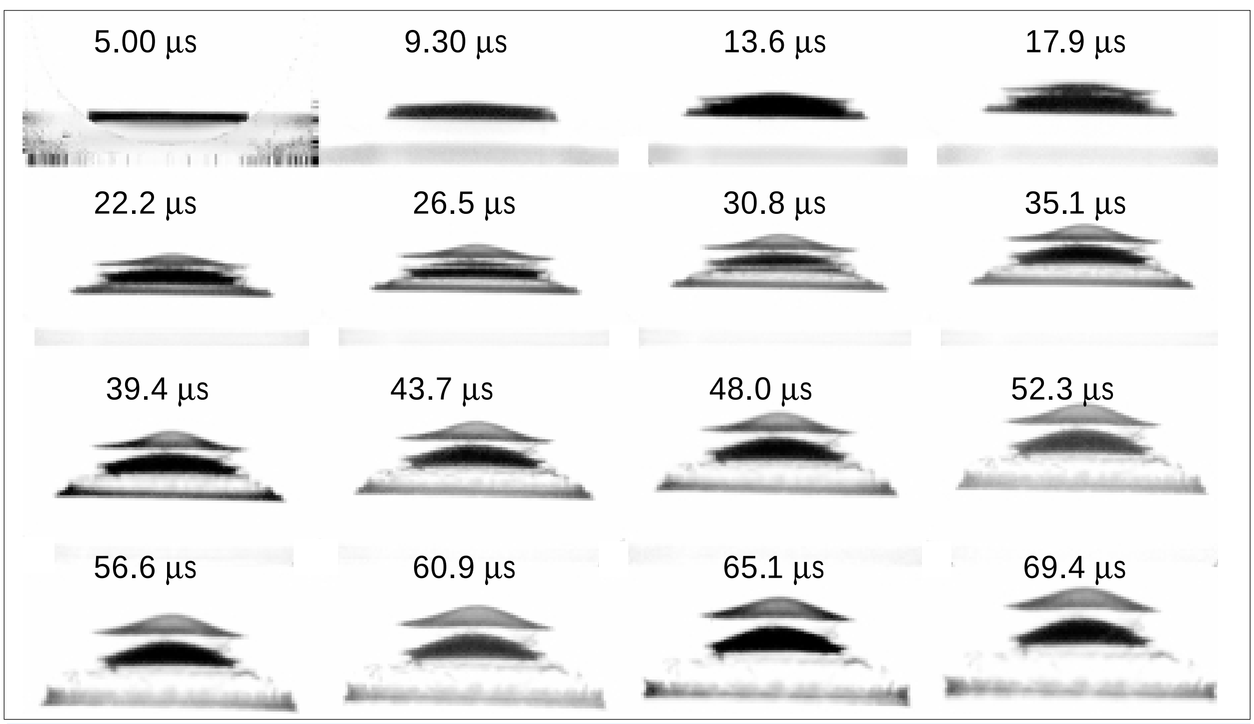


Fig. 1. *Schematic and three-dimensional rendering of HE spall experiment.*

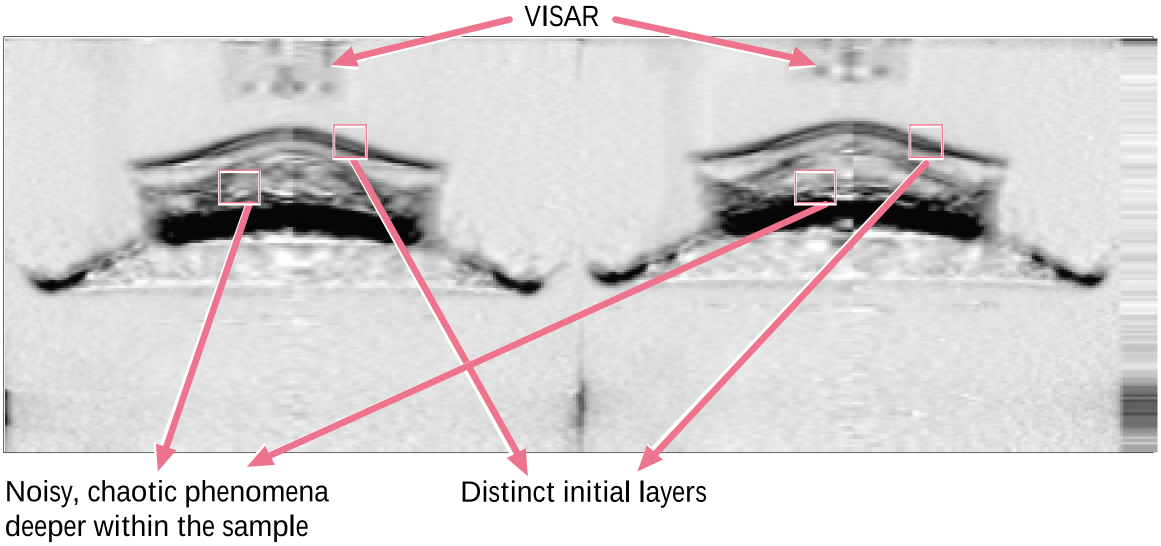
centered on the charge. Because the HE is point initiated, the shock wave has significant curvature. This "curved" geometry may be advantageous in pRad experiments since the integral of the proton path length is often shorter, and resolution and contrast may be improved, as compared to a pure "planar" geometry. The axial symmetry of the experiment is retained, however, which makes other advanced image processing possible (e.g., Abel inversions[2] used to produce "volume" density images). A velocity laser interferometer (VISAR) is also used to measure the time history of the surface during the experiment. Excellent agreement between VISAR and radiography results was obtained in all experiments to date. The "shutter time" of these proton radiographs is determined by the pulse width of protons that are used to produce each image frame. In these cases, the pulse width was typically ~ 50 ns, a short enough time to produce minimal motion blur (≈ 100 µm) even for the highest material velocity (aluminum at ~ 2 km/s).

Fig. 2 shows a series of 16 images of tantalum spall. This material has one of the highest spall strength of any material (~ 50 kbars). Spall strength is a measure of the strength of a tensile wave (in kbars) needed for the material to separate into layers. This strength is reflected in the exceptionally well-defined layers (and the small number of layers) visible. The times in Fig. 2 are relative to the time the detonator is initiated with a "fire" pulse. Note the curvature of the spall material and the complete separation of the material into layers. This can be observed even more vividly in "movies" produced from the 16 images. Copper provides an example of a material with an intermediate spall strength (~ 15 kbars). Fig. 3 shows a single image from two separate experiments at a comparable time (33.4 µs) after HE initiation. These images have been Abel[2] inverted to produce "volume" density images. Multiple spall layers are evident with the best-defined layers nearest the metal surface. As many as eight distinct layers are present in these images with defined velocities, although the layers become more "noisy," or chaotic, as one views deeper into the metal sample. It appears in Fig. 3 that the first few layers tear away smoothly as compared to the deeper layers. The more layers that tear away, the rougher, or "noisier," the spall phenomena becomes—a phenomenology we hope to one day understand. It is worth noting that these images, taken at nearly identical times, show quite good reproducibility, at least on the outermost layers. The VISAR optical probe is visible near the top of the frames.

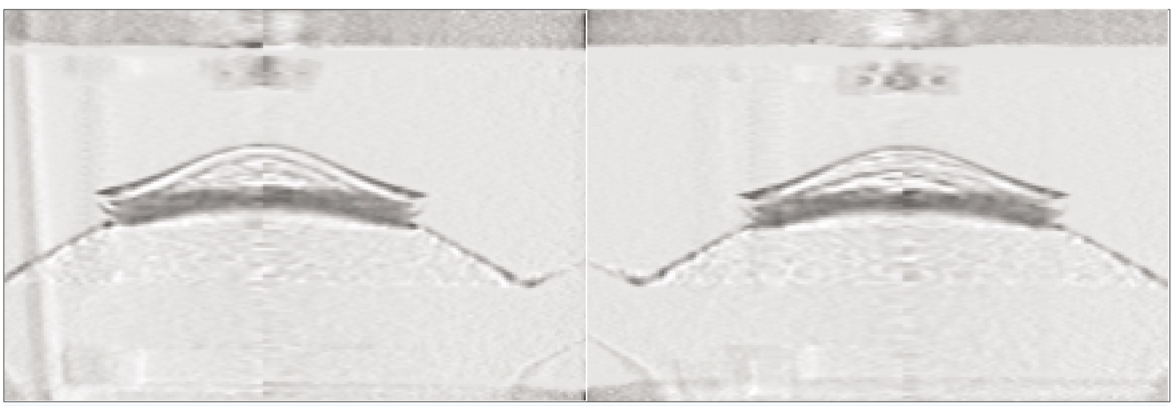
Fig. 4 shows a similar pair of experiments for aluminum 6061 at 19.0 µs. Because the atomic number of aluminum is low, the resolution and contrast of the radiographs are improved as compared to the copper and tantalum targets. Note the details of the VISAR optical probe that are visible in Fig. 4. The



↑ ***Fig. 2.*** *pRad images of HE-driven tantalum spall (areal densities), showing the evolution of the spall beginning with the top static image on the left and progressing to the right and down.*



↑ **Fig. 3.** *Abel-inverted "volume" images of copper spall from two separate pRad experiments at 33.4 µs. The VISAR optical probe, seen near the top of each frame, tracks the surface velocity of the first spall layer as it moves in response to the HE-induced shock wave.*



↑ **Fig. 4.** *Abel-inverted images of aluminum 6061 spall from two separate experiments at 19.0 µs after HE initiation.*

spall phenomenology in aluminum, however, is not as well behaved as in copper. The "turbulent" character of the deeper spall layers is visible after the first spall layer.

When the shock pressure is high, the material is melted after the shock wave reflects from the free surface of the metal target. Fig. 5 shows two frames at different times from an experiment on tin with the same HE configuration as the other experiments. The left-hand frame (at 19.3 µs) shows both ejecta produced when the shock reaches the metal surface. In the central region, the metal is melted (liquefied) upon the release and subsequent reflection of the shock wave at the surface, which appears more dramatically in the later image on the right (at 42.2 µs). The velocity of the melted material is substantially higher than the solid remnant left behind. This produces the dispersion of material observed.

Conclusion

Further analysis of these (and other) experiments is continuing. Our analysis is concentrating on how well we can measure the velocities, thickness, and other parameters of multiple spall layers with pRad and compare these results to both two-dimensional calculations and other non-radiographic spall diagnostics, such as the Assay Window.[3] We plan future experiments using higher magnification of the radiography to explore finer resolution details of the HE spall phenomenology.

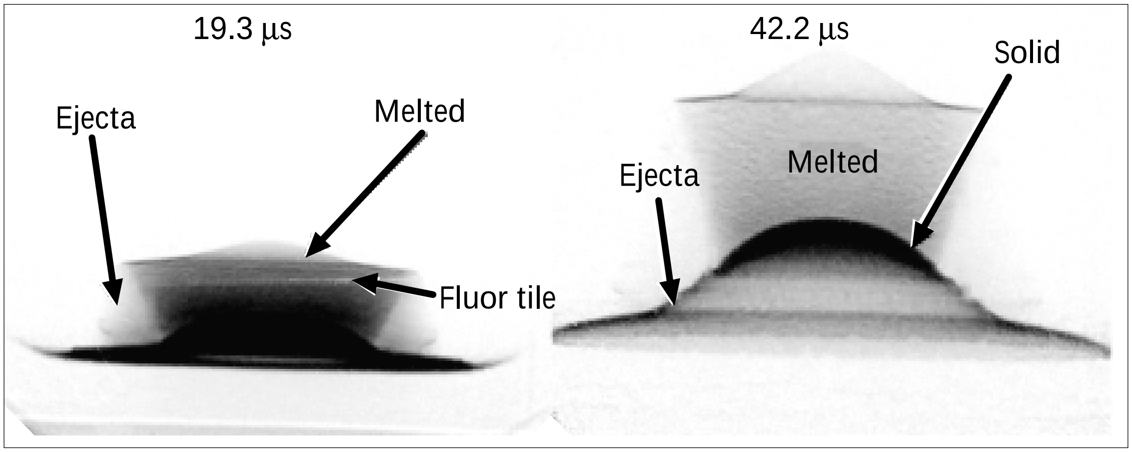


Fig. 5. *pRad images of shock-melted tin at 19.3 µs (left) and 42.2 µs (right); an artifact of the tiled fluor appears at the same image location in both.*

References

1. K.B. Morley *et al.*, "Proof-of-Principle Demonstration of Proton Radiography on a Dynamic Object," in *Proceedings of the 11th Biennial Nuclear Explosives Design Physics Conference* (1997); Los Alamos National Laboratory report LA-CP-98-6; and H.-J. Ziock *et al.*, "Using Proton Beams as a Radiographic Probe," Los Alamos National Laboratory report LA-UR-98-2660.
2. C. Morris, private communication (2001).
3. D.B. Holtkamp and W.F. Hemsing, "The Assay Window: Development of a Non-Radiographic Spall Diagnostic," (to be published).

For more information, contact David Holtkamp (P Division), (505) 667-8082, MS D410, dholtkamp@lanl.gov.

Produced by the LANSCE-4 communications team: Sue Harper, Grace Hollen, Barbara Maes, Sharon Mikkelson, and Garth Tietjen.

A U.S. DEPARTMENT OF ENERGY LABORATORY
Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36.

http://lansce.lanl.gov